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Modeling and simulating an electrical grid subsystem for power balance analysis ★

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Abstract: We present an approach for power balance analysis in Smart Grids where the physical behavior of different electrical devices is modeled at unit level, and the collective load and generation curves can later be obtained by aggregation. In this way, new behaviors, flexibilities and intelligent strategies for power consumption and generation can be easily introduced at the user-level and the system-level impact analyzed on the aggregated profiles. The future aim is to investigate bottom-up balancing strategies, where units with a flexible energy band can react independently to power balance signals such as dynamic prices.

Keywords: power balance, smart grid, modeling

1. THE GRID SUBSYSTEM

In the following, the term grid subsytem is used to refer to a geographical region of a national electrical network composed of low and medium voltage lines and the end-users, with only one connection to the high voltage transmission system.

The grid subsystem will be modeled as an aggregation of individual electrical units interconnected by the electrical network. Only the active power is considered and the electrical network is simplified to a summation representation (Fig. 1). While clearly incomplete, this simplification captures the first essential property of the electrical power system: power consumption must be met in real-time by the power production.

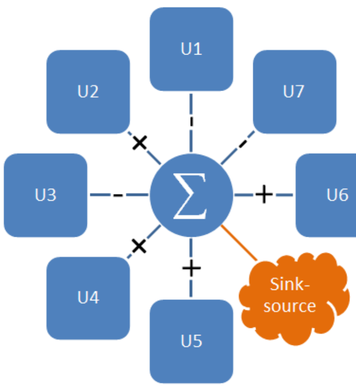

Fig. 1. Representation of a grid subsystem, where each U_i element is an electrical device and the summation element Σ represents the electrical network.

At every time instance, an individual unit connected to the grid is either a producer or a consumer of active power. The outputs of all units, producers (+) and consumers (-), need to be in balance. Whenever the sum is not zero, there is an instantaneous exchange through an external sink-source element that maintains balance. The sink-source has signification of an inter-regional electrical transmission connection. As anticipation, the external power exchange will be used as part of an optimization objective. For example, if the objective is to keep the subsystem independent of the interconnection link, then the optimal power exchange is 0.

Each electrical unit U_i operates independently and is composed of two systems: the service module and the physical device (Fig. 2).

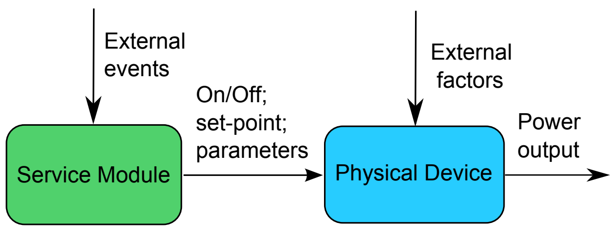

Fig. 2. Each electrical unit is composed of a physical device and a service module.

The physical device performs an energy converting task according to some configuration parameters and references, and operates under disturbances, such as weather and ambient factors. The output of the physical device is the electric power, either produced or consumed. The functionality will generally be modeled by employing first principles from physics, resulting in a mathematical description by differential equations.

The service module operates the "knobs and buttons" of the physical device, such as ON/OFF controls, parameters or reference settings. The service module is subject to external events but can also have internal logic or time plans. Modeling of the service module will include discrete event formalisms and stochastic elements.

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In a traditional grid, the power balance is maintained at the global level by a number of large capacity power generators with highly controllable characteristics and which can quickly adapt their power output to new levels. The baseline production and availability of these generators is planed ahead of time based on consumption and generation predictions. In the Smart Grid, the power balance control needs to be distributed in the grid to cope with increasing intermittent generation and increasing peaks in the load, and more end-users of electricity will take an active part in this process.

Some form of coordination is needed among the independent units in the SmartGrid to maintain power balance at the system level. We consider a feedback mechanism that shares a power balance signal from the global level to the local units. In particular, the power flow measured in the sink-source can be shared with the service module (Fig. 3). Flexibility profiles in the service module will make it possible to react to the balance signal within limits of local operation constraints.

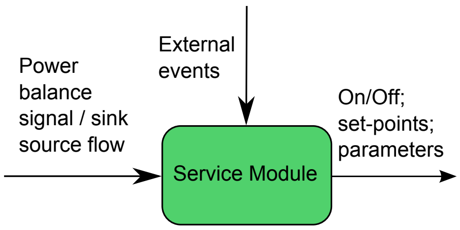

Fig. 3. The service module receives information about the global subsystem.

2. UNIT MODELS

This section presents simplified unit models for both power consuming and power producing devices with intermittent characteristics. It is mentioned that for the balance power problem only slow and mid-range dynamics are considered. Fast dynamics are assumed to be compensated by a grid frequency control scheme that is not discussed here.

2.1 Devices with externally driven ON/OFF states

Many types of electrical units such as lights, TVs, etc., have an ON/OFF operation that is directly driven by external events. This behavior can be represented as a continuous time stochastic process with a discrete state-space of two elements: $x = 1$ is the ON state and $x = 0$ is the OFF state.

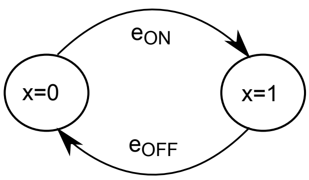

Fig. 4. The ON/OFF behavior

It is the occurrence in time of the events that is of particular interest. It can be considered that the ON and OFF events occur in a purely random manner, but with a varying frequency depending on the time of day. That is because, for example, it is more likely to switch a light in the evening than at midday. Two independent, nonhomogeneous Poisson processes will be used next to represent the arrival of the ON and OFF events. For an introduction to Poisson processes and the more general point process, we refer to Cox and Miller (1965).

Let Δt be a small time interval and $N(a, b)$ a variable counting the number of events occurring in the interval $(a, b]$. Looking in the small time interval Δt, there are three possibilities: no event, one event, or more than one event occurs. The probability of having more than one event occurring is very low, the probability of one event occurring is dependent on rate parameter varying with the time, and the probability remaining until 1 corresponds to the no event case. This is the definition of a nonhomogeneous Poisson process. The notation $o(\Delta t)$ below is used to denote terms which vanish with a small time interval, $\lim_{\Delta t \to 0} \frac{o(\Delta t)}{\Delta t} = 0$.

$$\begin{cases} \text{prob}\Big(N(t, t + \Delta t) = 1\Big) & = \lambda(t)\Delta t + o(\Delta t) \\ \text{prob}\Big(N(t, t + \Delta t) \geq 2\Big) & = o(\Delta t) \end{cases} \tag{1}$$

We let $\lambda_{ON}(t)$ and $\lambda_{OFF}(t)$ denote the variable rates of the two types of events. These can be taken as piecewise constant functions along the hours of the day, with different profiles for different devices. The ON/OFF mechanism together with the rate functions is enough for simulation purposes.

It is also of immediate interest to derive the probability distribution of the states, i.e. $\text{prob}_{x=1}(t)$, and also to characterize a group of devices in terms of number of units in state $x = 1$ at a given time. These will be addressed in the future work.

About the physical device modeling, when active, $x = 1$, the units included in this category can be considered to consume a constant amount of power although some loads can vary slightly, e.g. a radio for different volume settings, or a computer in idle mode versus while performing intensive computations. In a simple approximation, the power consumption p of a unit U will be written as:

$$p(t) = -cx(t), \tag{2}$$

where c is a device specific constant.

2.2 Space Heating and Cooling devices

This category contains units that are always in operation and the ON/OFF power consumption cycle is decided internally in the service module. Space heating devices operating on electricity, such as heat-pumps, air-conditioning units used for cooling and refrigerators are examples of devices with a switched operation based on thermostat settings.

As example, a simple model for a compressor cooled room is described below based on Tahersima et al. (2010), Halvgaard et al. (2012) and Hovgaard et al. (2010). It can correspond to a storage room that is kept at a lower temperature than the ambient. The physical system is composed of the cold room and the refrigeration system, as shown in Fig. 5. The notation is described in Table 1 below.

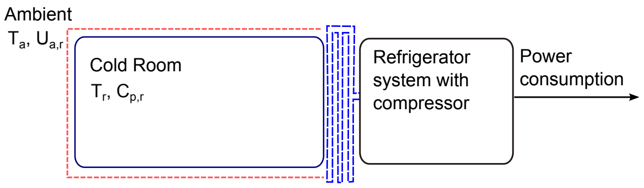

Fig. 5. A cooling system composed of a refrigeration system and a cold room in an ambient environment.

The physical system is described by the thermodynamic energy balance equation on the cold room.

$$C_{p,r}\dot{T}_r = Q_{a,r} - Q_{r,e} \tag{3}$$

The heat transfer between the ambient and the room $Q_{a,r}$ can be written as:

$$Q_{a,r} = \mathrm{UA}_{a,r}(T_a - T_r) \tag{4}$$

Table 1. Notation

T_a(t)	Ambient temperature, an uncontrollable but measurable, time varying value
T_r(t)	Cold room temperature
$C_{p,r}$	Heat capacity (at constant pressure) of the cold room
$Q_{a,r}$	Heat transfer from the ambient to the cold room
$\mathrm{UA}_{a,r}$	Heat tranfer coefficient (thermal resistance) between the ambient and the cold room

The assumptions here are that the temperature T_a and the heat transfer coefficient between the ambient and the room $\mathrm{UA}_{a,r}$ are known. Thus it is possible to calculate the evolution of the temperature in the cold room over time. By combining the equations, we can write the following description of the cool room in continuous-time variable T_r.

$$\dot{T}_r(t) = \frac{\mathrm{UA}_{a,r}}{C_{p,r}}\Big(T_a(t) - T_r(t)\Big) - \frac{Q_{r,e}}{C_{p,r}} \tag{5}$$

The decision logic module is related to the start and stop of the compressor. The ON/OFF behavior from Fig. 4 applies also to the cold room, where the events e_{ON} and e_{OFF} have the triggering mechanism

$$\begin{cases} T_r > T_{ref+} \rightarrow e_{ON} \\ T_r < T_{ref-} \rightarrow e_{OFF} \end{cases}, \tag{6}$$

with T_{ref+} and T_{ref-} temperature thresholds, parameters of the service module. When activated, the power consumption of the compressor is considered constant.

$$p(t) = -c\,x(t) \tag{7}$$

The only information missing is a relation that describes the amount of heat absorbed by the refrigerator system from the cold room $Q_{r,e}$. This relation depends on the properties (performance) of the refrigeration cycle, the compressor state, and a heat transfer constant with the cold room, but is not expanded at this point.

Additionally, a stochastic term can be added to the dynamic description (5) to account for other heat transfer processes occurring in the cold room, for example doors opening and small variations in the overall heat capacity of the room. Such a model, and also results for the aggregated consumption of a groups of similar devices, are considered in Malhame and Chong (1985) and Malhame (1990).

2.3 Wind turbines

There are different types of devices that generate electrical power from wind. In this section we consider the most common wind turbine design, the horizontal axis machines with 3 blades, operating independently. Wind-farms models will be addressed in future work.

Every type of turbine has a static power curve characterization. The power curve relates the electrical output of the turbine to the input wind-speed, as shown in Fig 6.

The power curves are poor predictors for the instantaneous power output as they do not contain any information on the dynamics of the turbine subsystems nor references about the fluctuations of the wind, but they are a good representation as an average behavior over longer periods of time. Power curves will be used here as an approximated model because they have the advantage of being easily available for different turbine models, and can be used for all types of turbine designs.

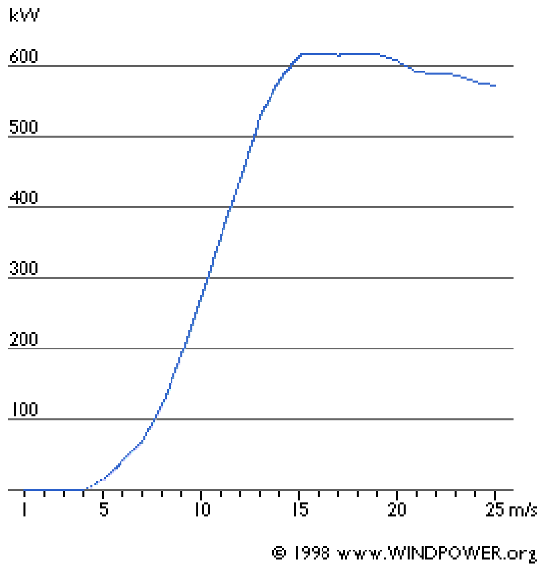

Fig. 6. Power curve for typical Danish 600 kW turbine with stall control, from www.windpower.org

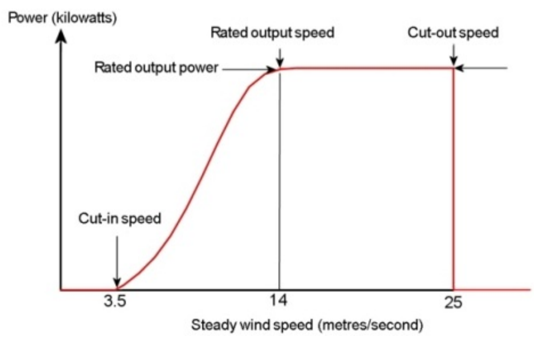

Fig. 7. Typical power output with steady wind speed for a pitched controlled turbine, www.wind-power-program.com

A simple service module for wind turbines is described next. The wind-turbine generator is OFF for wind-speeds under 5m/s, ON and tracking the power curve for wind-speeds smaller than 23m/s. If the wind-speed exceeds this value, the turbine is stopped. Besides wind-farms, medium size CHPs (combined heat and power plants) and solar panels will be addressed in future work.

3. FUTURE WORK ON SCENARIOS AND SIMULATION

A scenario will contain multiple units of different types, e.g. 2000 light units, 100 ground heat pump devices, and 20 wind turbines. It possible to create a scenario using real data from a geographical region provided sufficient information is available on the number and characteristics of the consumers and producers in the area. Observational data on air temperature, solar irradiation and wind is available from different weather stations in the world, including Denmark. By running software simulations, daily and monthly aggregated load and generation curves are produced. The comparison of aggregated curves from the simulation with those from real data, in terms of main trends, will serve as model validation for the both unit models and the aggregation methods.

The purpose of the scenarios is to test different user-level energy strategies and investigate how the local behaviors scale up and affect the electric power balance of the subsytem.

For example, the temperature thresholds of the refrigerator thermostat can be changed in response to a power balance signal, within the limits permissible for the cold room operation. When the grid subsystem has an excess of power, the service module of the refrigerator system can lower the temperature of the cold room by reducing the threshold values T_{ref-} and T_{ref+}. The compressor will consume more power, but will do so at an advantageous time, when the costs are lower and energy can be stored locally for later use. When there is a deficit of power, the service module can choose to reduce the use of the compressor and increase the threshold temperatures. This simple strategy appears to be "smart" at user level, but needs to be validated against an aggregated scenario, as it can have pitfalls. When more than one devices react in real-time to the same signal, it is possible that the system over-reacts and an imbalance of the opposite sign is created. Also the local effect of the strategy over time can turn out not to be beneficial. Increasing the threshold temperature can be too costly over time if more power needs to be consumed at inappropriate times for recovery.

For wind turbine systems, the service module can run a delta control (nominal underproduction) which allows for a band of flexibility. The turbine will produce less in normal operation, but has the possibility of compensating in power deficit situation. By analyzing scenarios it will be possible to evaluate when this trade-off is sufficient to assure the stability of the subsystem.

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